VERITAS Stellar Intensity Interferometry (VSII) 2024

Dave Kieda
University of Utah
For the VERITAS Collaboration

Sept 11, 2024

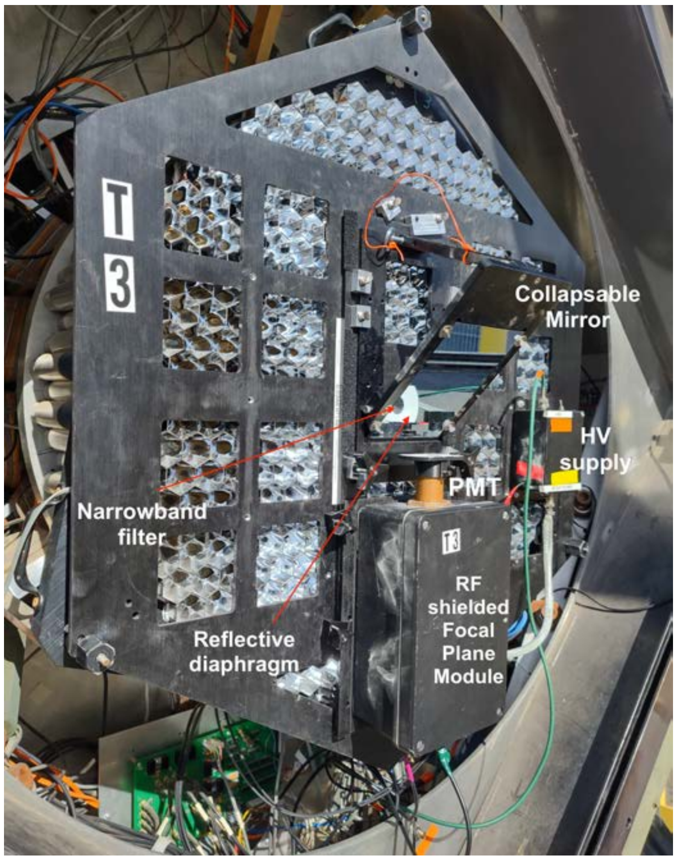
VERITAS-SII (VSII)

- Excellent instrument for SII
- Large photon collection area (~12 m Ø mirrors)
- 40 m to 150m baselines
- Optically isochronous (< 4 ns)
- 250 Mhz photocurrent sampling
- Telescope time available during Full Moon

Sub- milliarcsecond optical resolution @ 400 nm

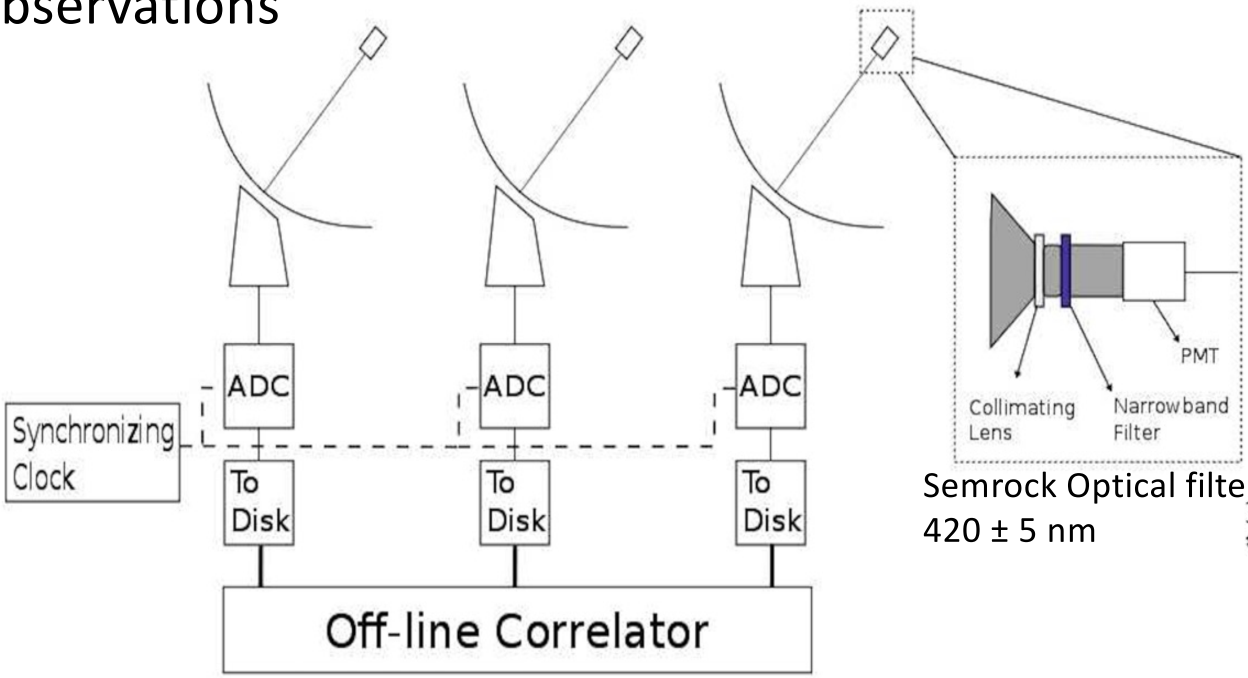
- Multiple science topics
- Pathfinder for km-scale arrays (CTA-SII)

Removable VSII Camera Plates

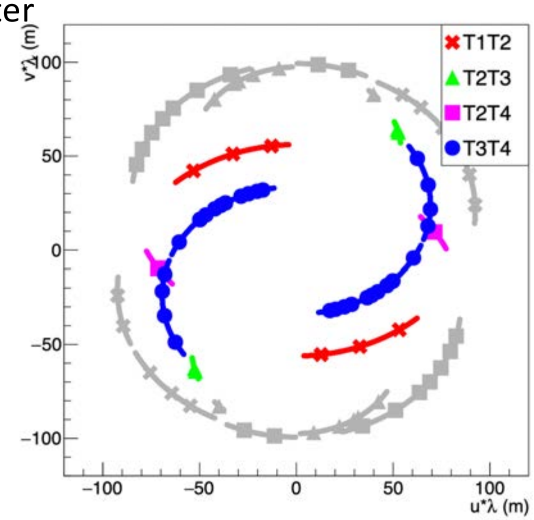


- The removable VSII Camera Plate mounts in front of the VERITAS Camera focal plane.
- Observer locates the VSII Plate onto each camera at beginning of full-moon period.
- Plate contains necessary focal plane optics, HV supply, photomultiplier and preamplifiers to perform VSII measurements.
- Quick connect to cables for signal, power, control
- At end of run the VSII plate is removed and stored in dust-proof box.
- About 20 minutes to install each plate

VSII Observations



Semrock Optical filter
420 ± 5 nm

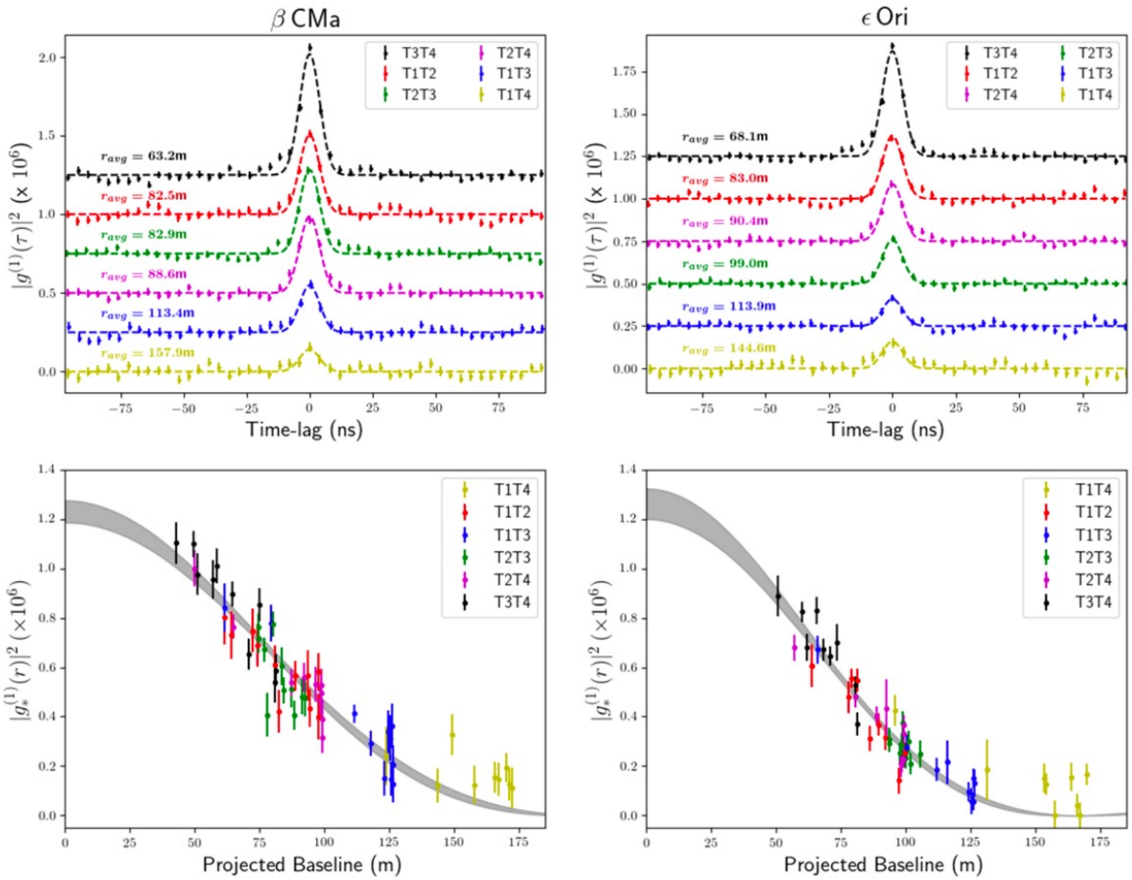


VSII Sampling of Fourier Image Plane

$$\frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle} = g^{(2)}(u, v, t) = 1 + \left| g^{(1)}(u, v, t) \right|^2$$

$$g^{(1)}(u, v, 0) = \iint I(l, m)\, e^{-2\pi i (lu + mv)} dl\, dm$$

$I(l, m)$ is the stellar image size and brightness distribution on the sky



0.5 mas angular size
"Basketball on the moon"

Source	θ_{UD} (mas)	T (h)	θ_{UD} (mas)	T (h)
β CMa	0.50 ±0.03	63.4	0.523 ±0.017	5.5
ϵ Ori	0.67 ±0.04	56.0	0.631 ±0.017	4.25

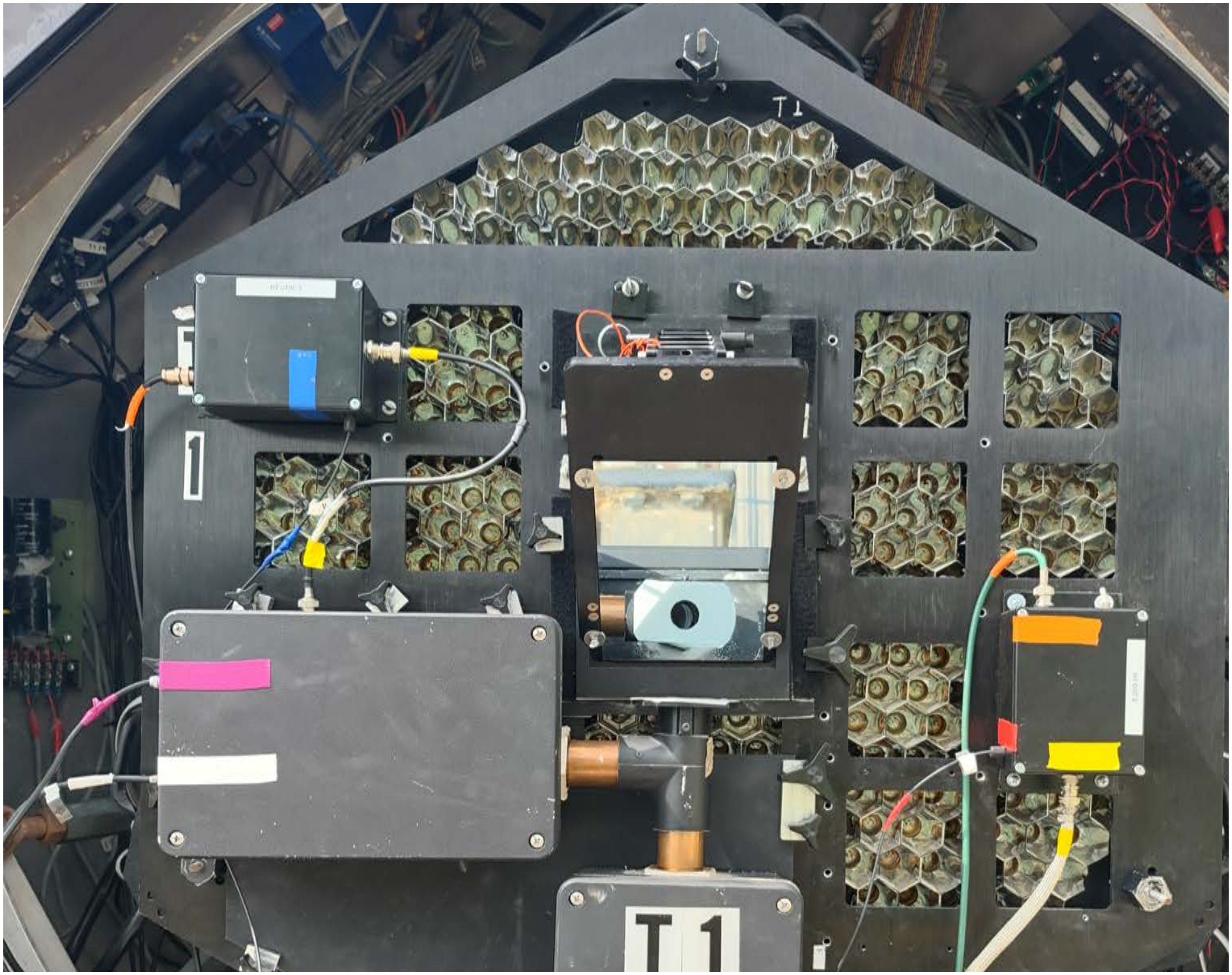
(T= Observation Time)

Narrabri SII
Observations 1970

VERITAS-SII
Nature Astronomy 2020

A. Abeysekara, Nature Astronomy 2020

VSII Observatory Status

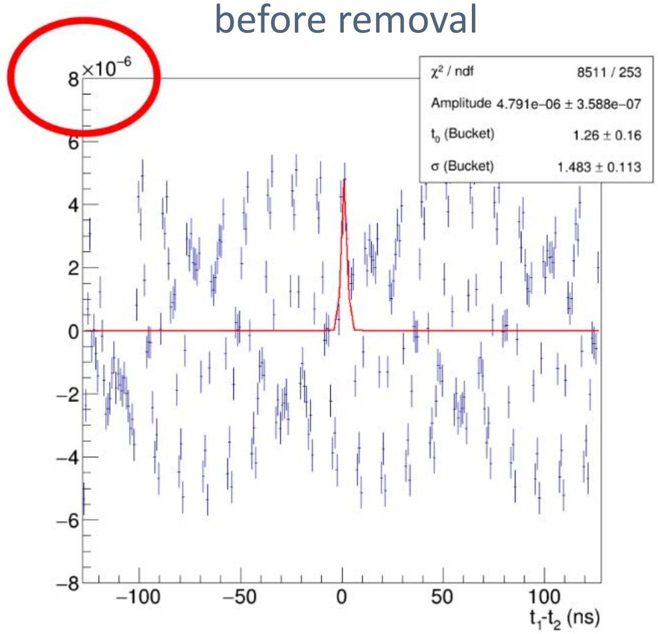


VSII System Status

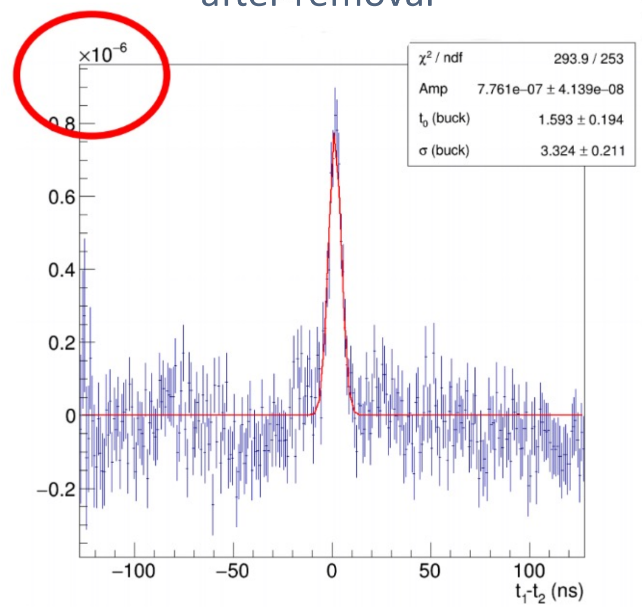
- All SII Plates modified to use Power Tool Batteries (December 2023)
  - Works 4+ days without recharging
  - Easy to replace/inexpensive – available at Home Depot
- Upgraded anti-aliasing low pass filters to improve electronic response (less ringing)
- Added sufficient disk space for 12+ nights of continuous observations
  - 120+ TB/telescope
- DAQ Systems extremely stable (4+ hour continuous observation routine)
- Data Transport network improved (10 G throughput/telescope)
- VERSII Correlator (Ohio State) is the primary correlator now
  - Process all (6) observation pairs in near-real time
- Telescope positions remeasured using RTK receiver (>1 m error reduced to < 1 cm)
- Current instrumental focus :
  - RF Noise reduction (optical fiber analog signal transport)
  - Improved absolute peak timing (< 1 nsec)
  - Simplified array operations software
  - VERITAS Mirror recoating

Whipple Observatory 79 MHz Noise

before removal



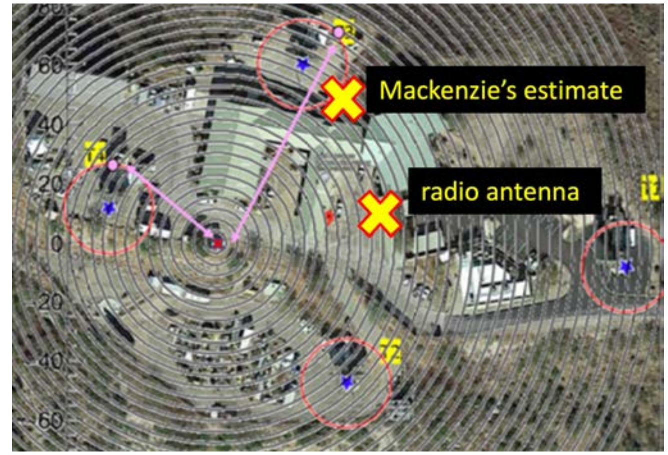
after removal



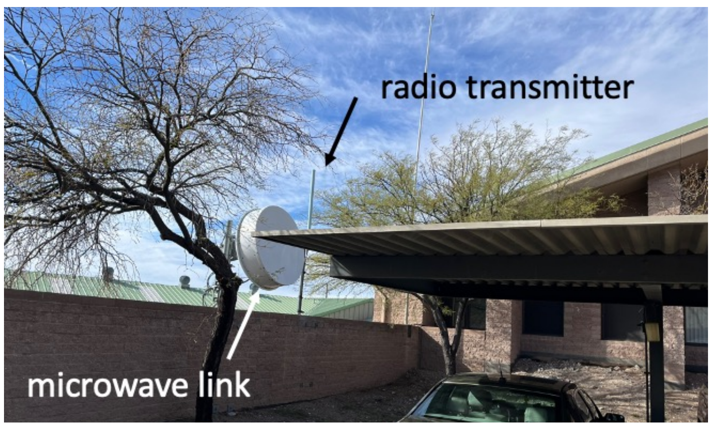
- Occurs Only at Whipple Observatory
- 79 MHz noise seen in all Four VSII Telescopes
- Additional (much weaker) RF frequencies seen at Tucson FM radio bands
- Removed by software processing so allow visibility analysis

FLWO 79 MHz Noise (2024)

- Source of the 79 MHz noise is identified as the basecamp radio repeater at 171.4 MHz
- Appears as 79.4 MHz through aliasing by 250 MHz VSII sampling
- Seveal Possible remediation methods

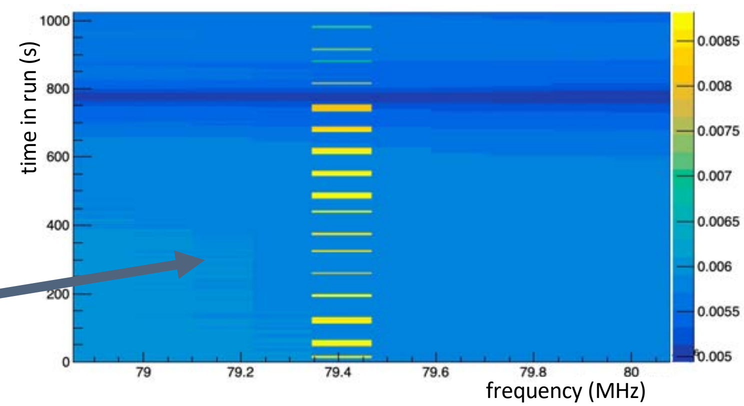


Results of 2021 study by Mackenzie (Scott)
Ticoras very close to actual source of noise



79 Mhz is episodic: Occurs in 20-35% of data frames (work from John Scott, OSU)

Due to periodic radio broadcast query (adjustable)



Update Sept 2024: FLWO staff will reduce cadence or stop broadcast queries during nighttime observations

The Ohio State University

Versii – dedicated correlator server

Funded by NSF MRI

DELL PowerEdge 750 Server
RedHat Enterprise Linux 8

Two Intel Xeon Platinum 2.3 GHz CPUs

- 40 cores (hyperthreaded) *each* – **80 cores total**

GPU-ready; single Nvidia Tesla T4 for prototyping

6 Gbps SATA SSDs

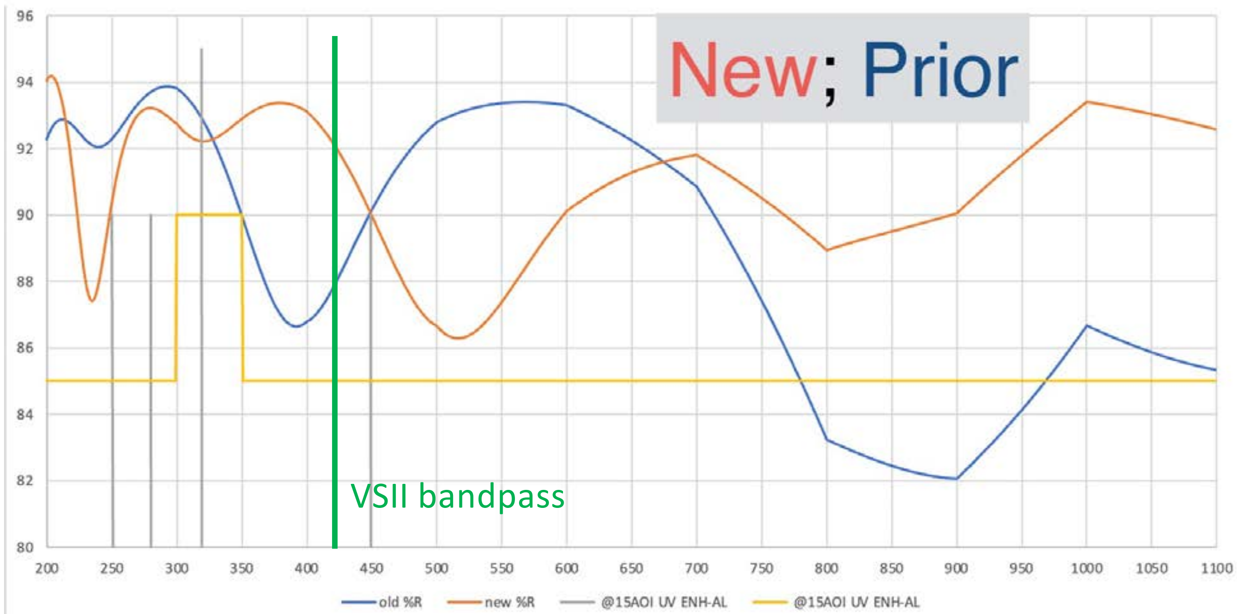
- 2 x 480 GB
- 10 x 3.84 TB in 2 x RAID-0

On-site power & cooling upgraded

T4: Black Object at 2F

VERITAS Mirror recoating underway (2023-2025)

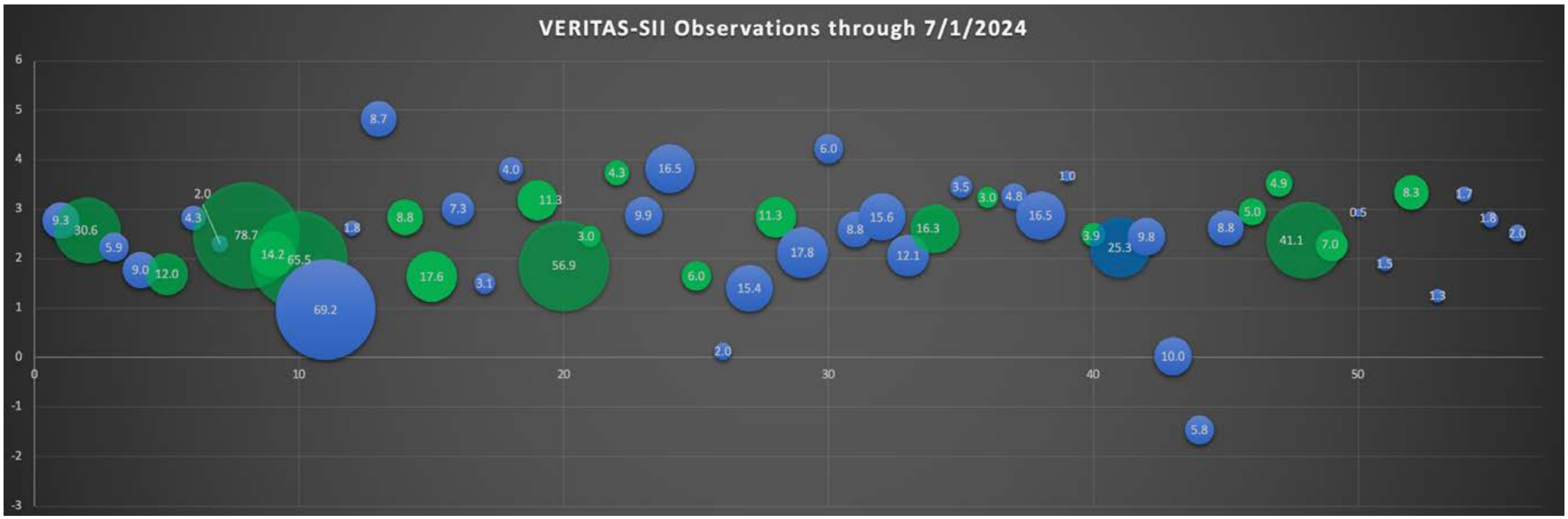
Mirror recoating by commercial vendor (DOTI, Round Rock, TX)



1) Mirror Recoating increases overall telescope mirror reflectivity by 20%
2) New DOTI coating formula increases reflectivity at VSII bandpass (420 nm) by additional ~5%

VSII Observations (Jul 1, 2024)

m_V



Primary star classification O9 O9.5 B0 B0.5 B1 B2 B3 B7 B8 B9 A0 A1 A2 A8

Single star

Binary/multiple star

Circle area is the number of each star's exposure (hrs) (12/1/19 – 7/1/24)

- 56 different targets
- 33 single
- 23 binary/multiple
- Total 732.3 hrs exposure
- 125.8 hours 2023-2024 obs season

Key Science Motivators for SII

- Stellar diameters, winds, photosphere structure
- Rapid Rotators, Cepheid variables
- Resolving Binary Systems, accretion disks
- Stellar Novae (transient events)
- Astrophysical lasers and emission lines

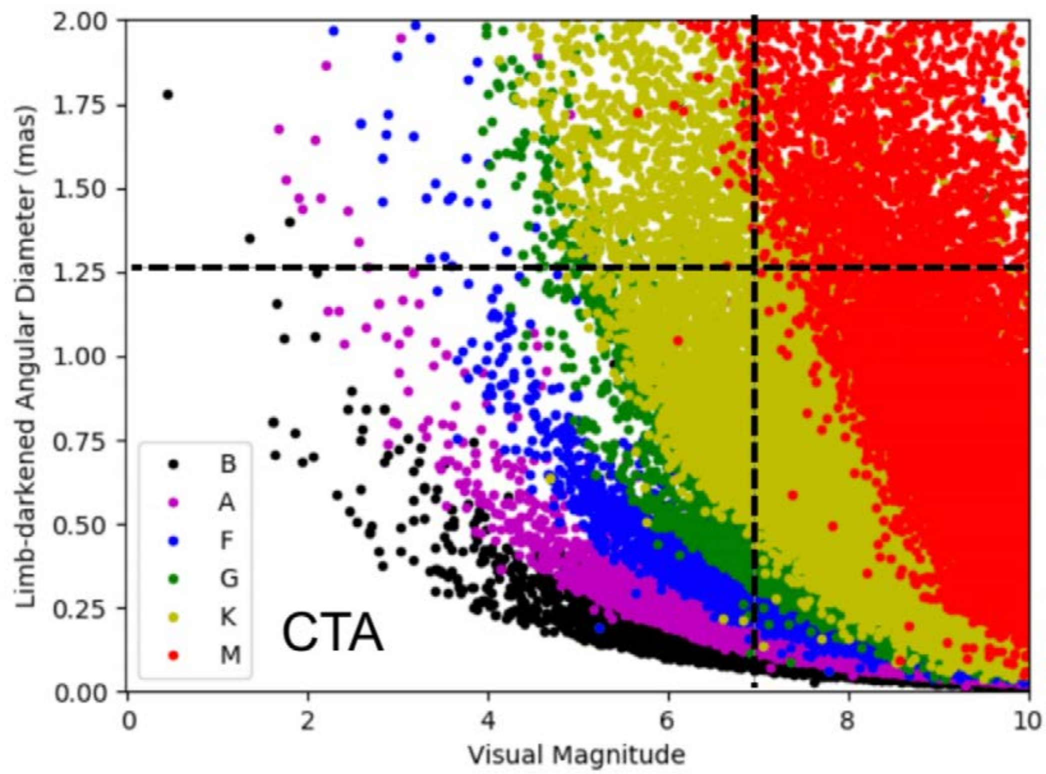
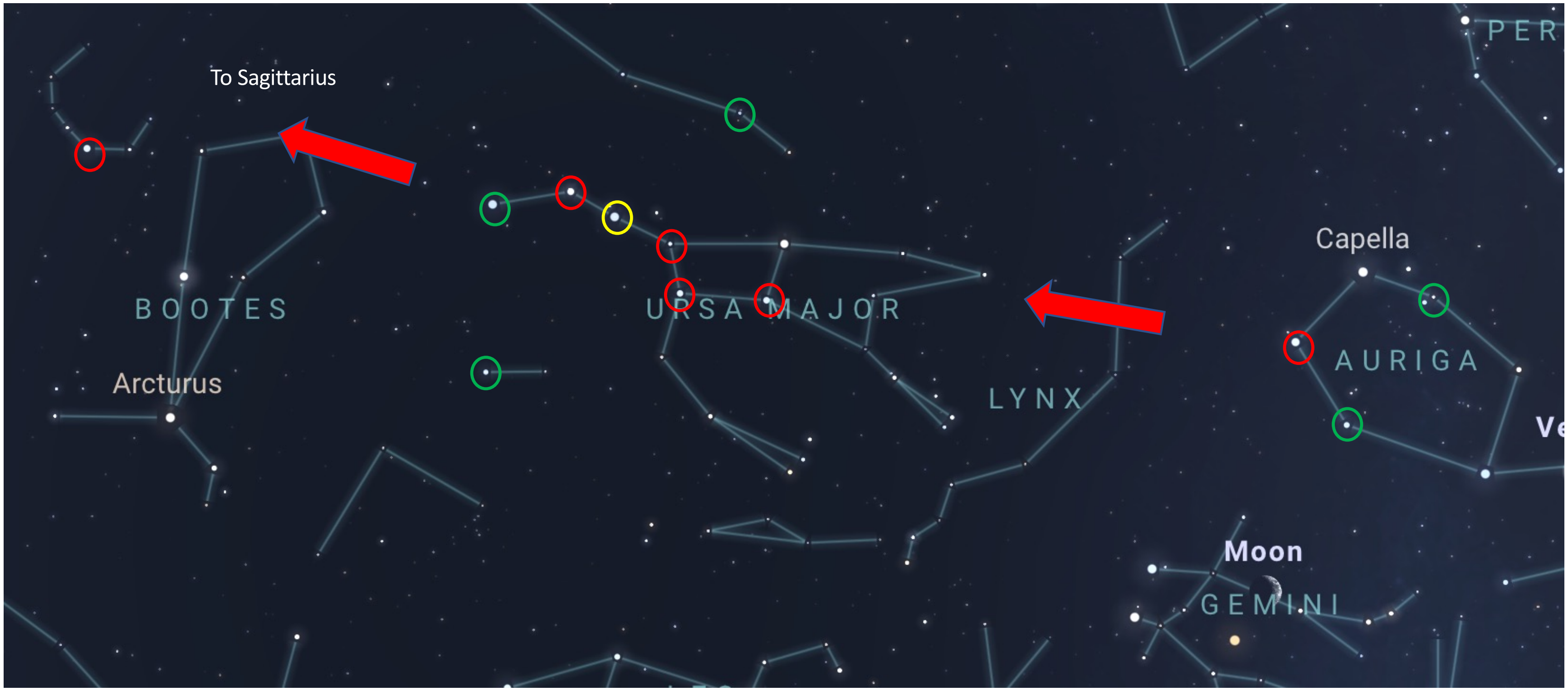


Image credit: N. Matthews (JSDC Stellar Catalogue)

VSII Observations Near Ursa Major



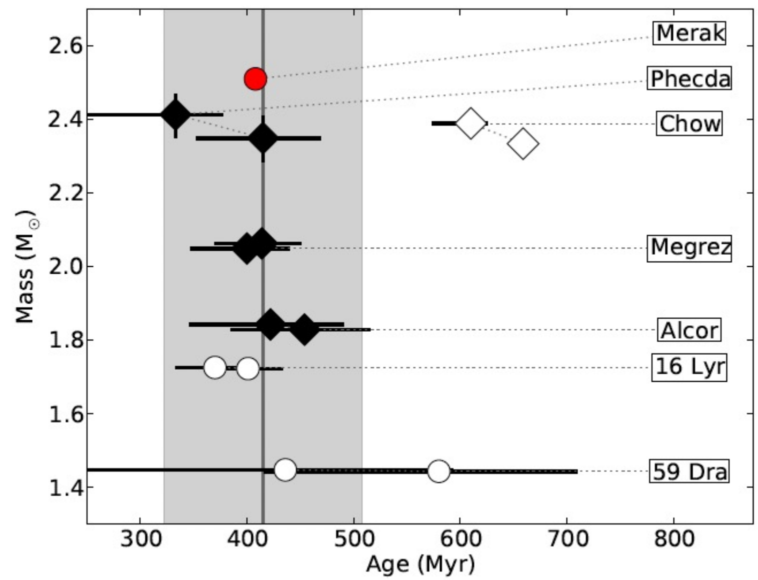
Ursa Major Moving Group

- 25 psc away
- 15 stars in Ursa Major nucleus
- 47 stream stars outside nucleus
- Common 15 km/sec motion towards Sagittarius
- Origin in open cluster formed 500 My ago
  - All are A stars or cooler
  - CHARA observation provide tightest age constraints
  - Some potential issues with fast rotators

A 3% constraint in θ_{LD} *by VSII measurement gives (post-MS star)*

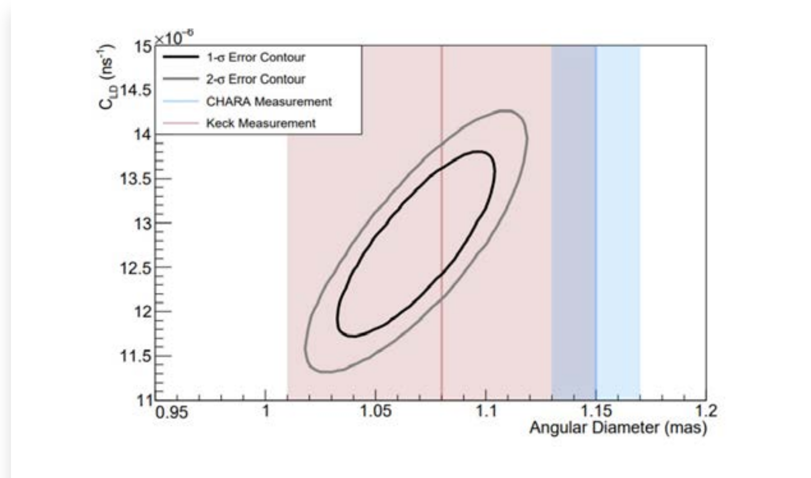
- *1.5% constrain on* T_{eff}
- *6 % constraint on* t_{age}
- *0.6% constraint on* M_{star}

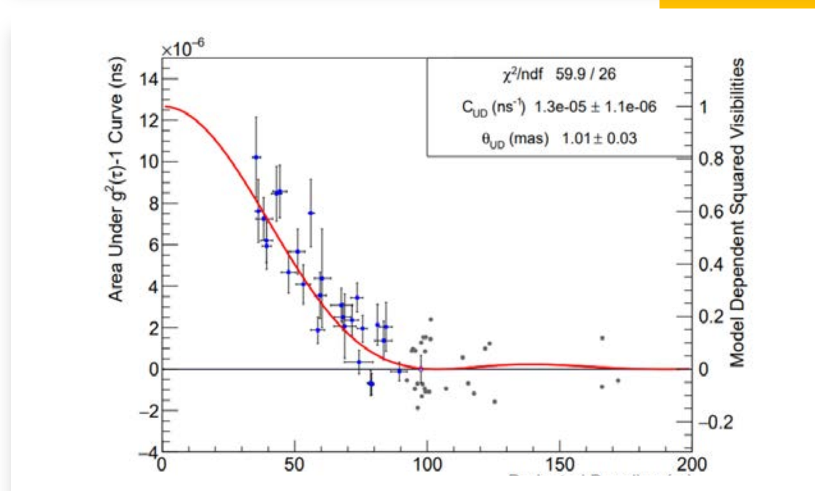
10-20% constraint



J. Jones, CHARA Collaboration (Ap. J, 2015)

VSII- Merak Analysis





- 37.4 hours, 4 Telescope observations (12/21-3/22)
- 2 independent analysis (standard & Bayesian)
- Measured age: 390 Myr – Slightly younger, Smaller radius, hotter temperature, better match to UV spectra

A. Acharyya et al, Ap. J 966, 1, 28 (2024)
arXiv:2401.01853

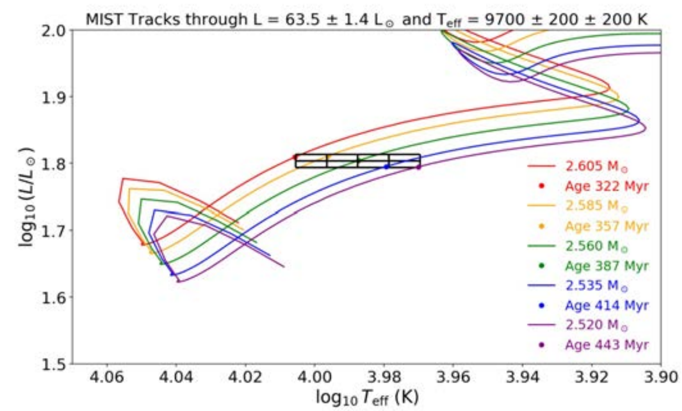
Stellar Properties

- Using previously measures quantities and MESA stellar evolution models we can compile various fundamental properties for this star including age.

- Our measured age (390 ± 29 ± 32 Myr) is consistently lower than the age measured by CHARA (408 ± 6 Myr) due to our smaller angular diameter (hotter star).

Table 3. Fundamental Stellar Parameters for β UMa

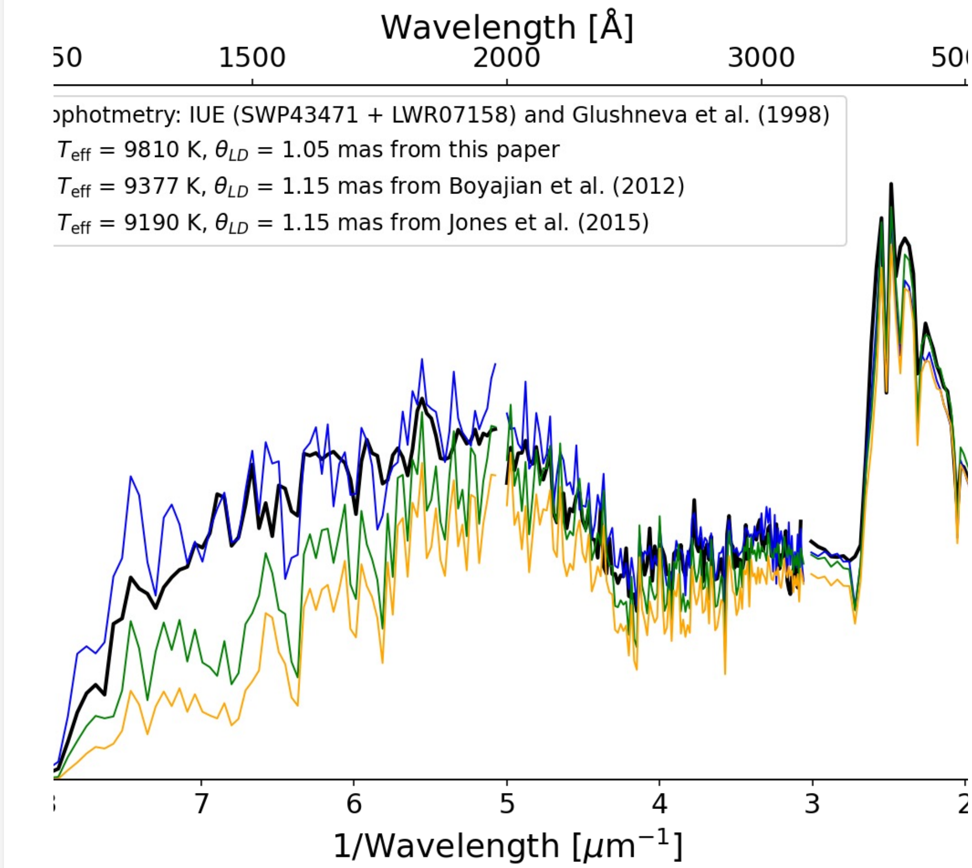
Parameter	Value	Reference
Limb-darkened angular diameter, $\theta_{\rm LD}$ (mas)	$1.07 \pm 0.04 \pm 0.05$	This paper
Bolometric flux at Earth, $F_{\rm bol}$ (erg s^{-1} cm^{-2})	$(340 \pm 7) \times 10^{-8}$	Boyajian et al. (2012)
Effective temperature, $T_{\rm eff}$ (K)	$9700 \pm 200 \pm 200$	derived, $[4F_{\rm bol}/\sigma\theta^2_{\rm LD}]^{1/4}$
Parallax, ϖ (mas)	40.90 ± 0.16	van Leeuwen (2007)
Radius, R ($R_\odot$)	$2.81 \pm 0.11 \pm 0.13$	derived, $\theta_{LD}/2\varpi$
Luminosity, L ($L_\odot$)	63.5 ± 1.4	derived, $4\pi F_{\rm bol}/\varpi^2$
Mass, M ($M_\odot$)	$2.56 \pm 0.03 \pm 0.02$	MIST tracks (Dotter 2016; Choi et al. 2016)
$\log_{10}$ surface gravity, $\log g$ (cm s^{-2})	$3.93 \pm 0.03 \pm 0.05$	derived, $g = GM/R^2$
Age (Myr)	$390 \pm 29 \pm 32$	MIST tracks (Dotter 2016; Choi et al. 2016)
Projected rotational velocity, $v \sin i$ (km s^{-1})	47 ± 3	Royer et al. (2002)



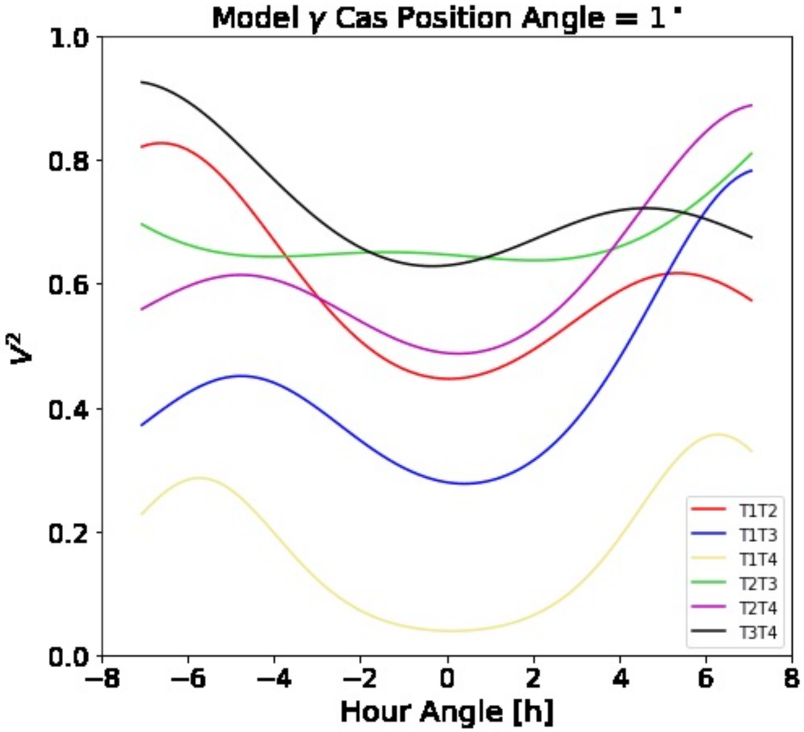
Stellar Spectra

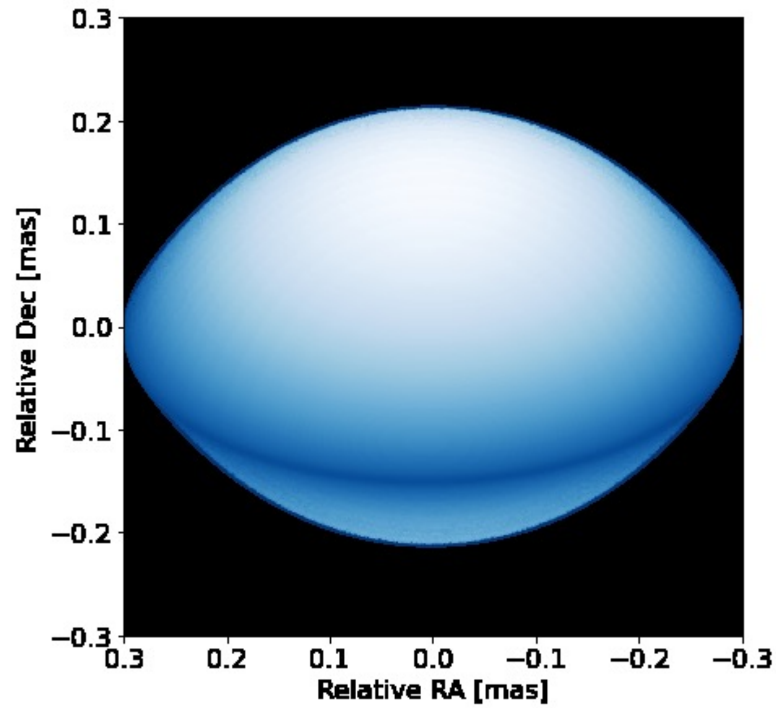
- VSII Smaller Merak Diameter -Requires hotter star
- Simulated Merak UV spectra better matched to observations

J. Aufdenberg et. al 2024



New VSII Results 2024





Prasenjit's Classification:

"Awesome" Results…

Measuring photosphere of a Fast Rotator

See Josie Rose's Talk (Next)

New VSII Results TBD

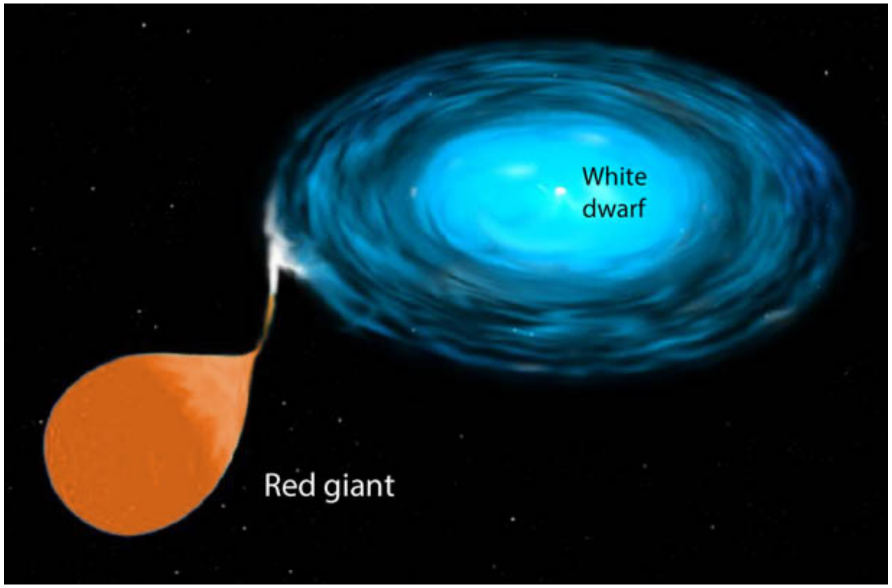
Prasenjit's Classification

"High Risk-High Return"

Results…..TBD

Recurrent Novae

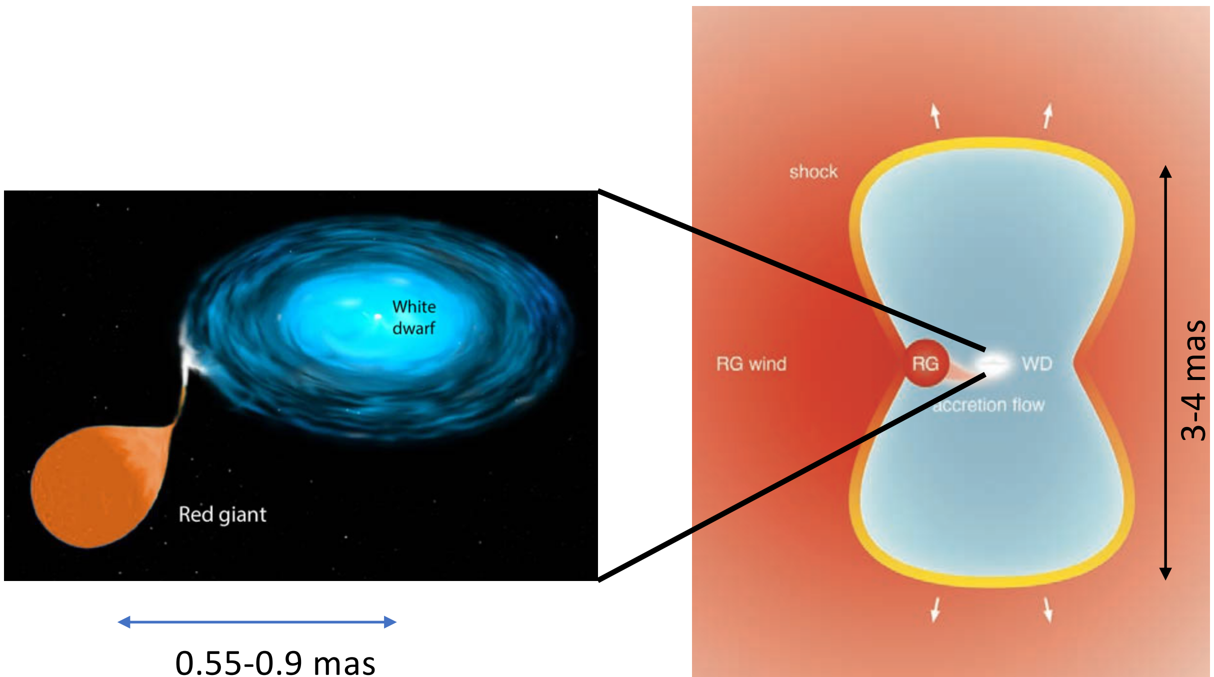
Full name	Discoverer	Magnitude range	Days to drop 3 magnitudes from peak	Known eruption years	Time span (years)	Years since latest eruption
CI Aquilae	K. Reinmuth	8.6–16.3	40	1917, 1941, 2000	24–59	23
V394 Coronae Australis	L. E. Erro	7.2–19.7	6	1949, 1987	38	36
T Coronae Borealis	J. Birmingham	2.5–10.8	6	1866, 1946	80	77
IM Normae	I. E. Woods	8.5–18.5	70	1920, 2002	≤82	21
RS Ophiuchi	W. Fleming	4.8–11	14	1898, 1907, 1933, 1958, 1967, 1985, 2006, 2021	9–26	2
V2487 Ophiuchi	K. Takamizawa (1998)	9.5–17.5	9	1900, 1998	98	25
T Pyxidis	H. Leavitt	6.4–15.5	62	1890, 1902, 1920, 1944, 1967, 2011	12–44	12
V3890 Sagittarii	H. Dinerstein	8.1–18.4	14	1962, 1990, 2019	28–29	4
U Scorpii	N. R. Pogson	7.5–17.6	2.6	1863, 1906, 1917, 1936, 1979, 1987, 1999, 2010, 2022,	8–43	1
V745 Scorpii	L. Plaut	9.4–19.3	7	1937, 1989, 2014	25–52	9



Bradley E. Schaefer 2010 *ApJ S* **187** 275

https://en.wikipedia.org/wiki/Nova#Recurrent_novae

RS Ophiuchi- A recent recurrent nova



d = 1.6-2.5 kpc
T_{orbit}= 453.6 days

M_{WD}=1.2 - 1.4 $M_\odot$
M_{RG} = 0.68-0.8 $M_\odot$
Inclination i= 49-52°

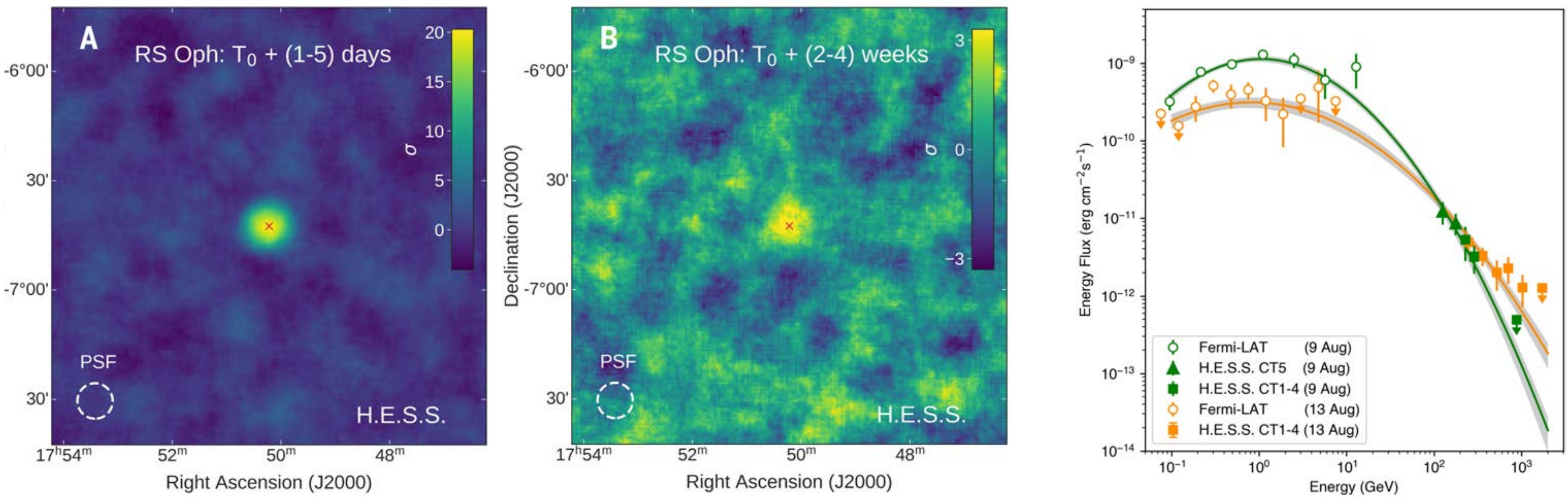
a sin i = 240 $R_\odot$ = 1.12 AU = 5.4x 10^{-6} pc

Ang Separation = 0.55-0.9 mas

Recurs ~15-20 years (V = 4.8)

Recent eruptions: 2006, 2021

RS Ophiuchi 2021- A Recurrent Nova



Detected in
TeV Emission: HESS, MAGIC, LST-1
GeV Emission: Fermi

HESS COLLABORATION, SCIENCE Vol 376, Issue 6588 pp. 77-80
DOI: 10.1126/science.abn0567

d = 1600-2500 pc

n.b. VERITAS could not observe due to summer monsoon

RS Ophiuchi – angular size

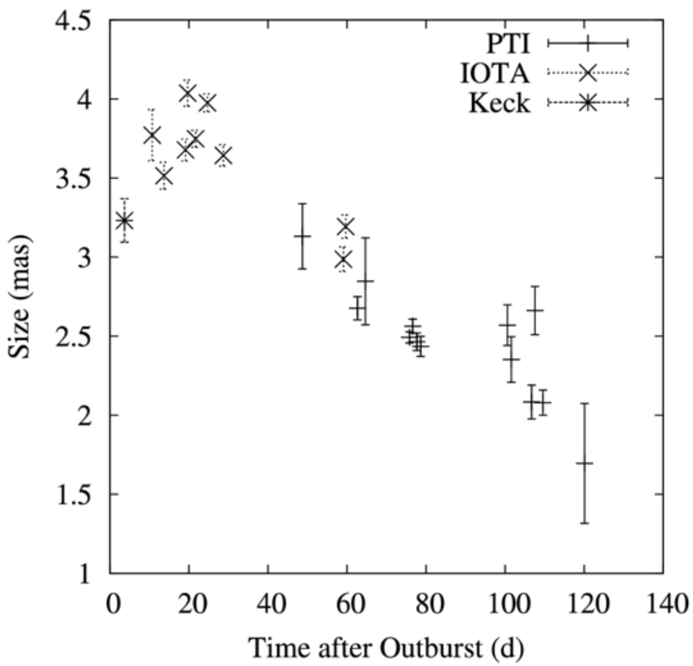


FIG. 2.—Best-fit night-by-night angular diameter of the major-axis of Gaussian emission model, with the orientation and position angle constrained to the overall best-fit values explained in the text.

B.F Lane et al. , Ap J 658, 520 (2007)

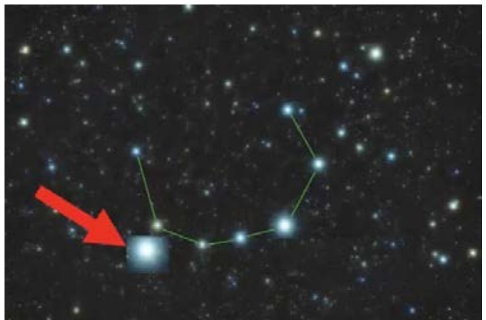
Angular size of emission region (3-4 mas) measured by amplitude interferometers in IR during a previous burst (2006)

- >> RG-WD separation (0.5 mas)
- time dependent
- reaches maximum ~ 20 days

An expanding and contracting emission/shock region

n.b. …this outburst predates VERITAS, MAGIC, HESS, LST….

T Coronae Borealis: Another recurrent nova



Symbiotic Binary: RG + WD
M_{WD}=1.37 $M_{\odot}$
M_{RG} = 1.12 $M_{\odot}$

Distance = 806 pc

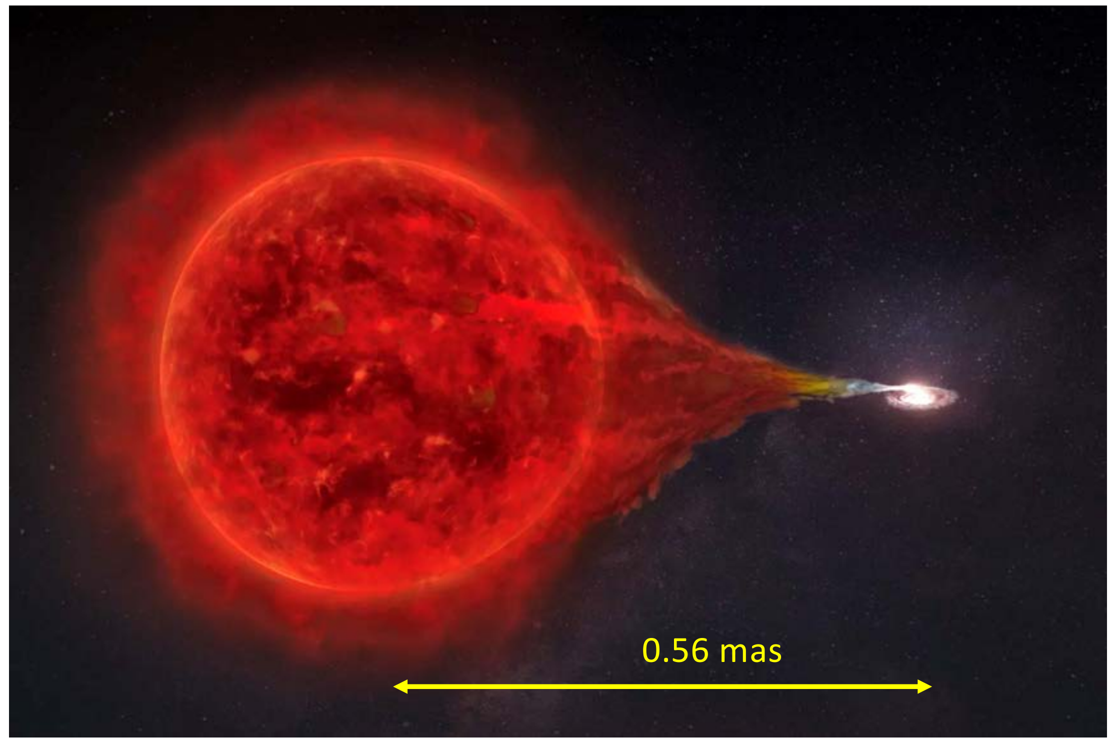
Orbital Period = 227 day
separation a = 0.54 AU
eccentricity = 0
inclination i = 67^0

Angular separation = 0.56 mas

Quiescent V = 10+

Recurrent Nova (V= 2.0) every ~80 years
Predicted Eruption: 2024.4 +/- 0.3 (Still waiting for it!)

“Recent” Outbursts 1866, 1946
Some Evidence of Outburst 1787, 1217(!)
[See Brad Schafer’s Sep 2023 AAVSO YouTube talk]



NY Times article 3/7/2024: https://www.nytimes.com/article/nova-new-star-t-coronae-borealis.html?searchResultPosition=1

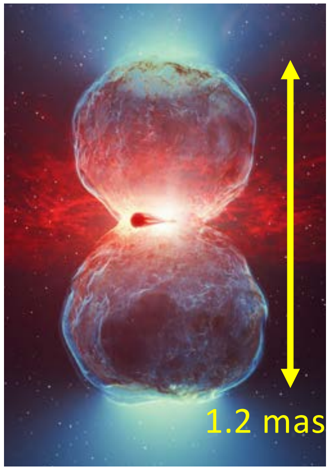
T Cor Bor Expansion Time

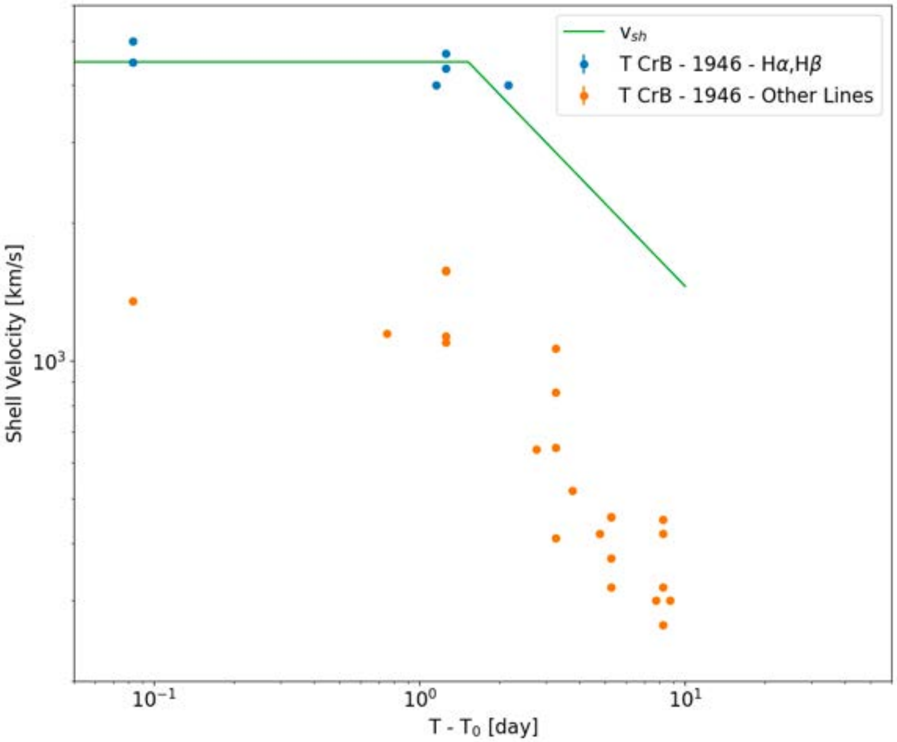
Hα , Hβ ~ 4000 km/sec
Expansion to 1.2 mas
~8 hours

But N, O, Si, Fe ~ 1000 km/sec
32 hour expansion?

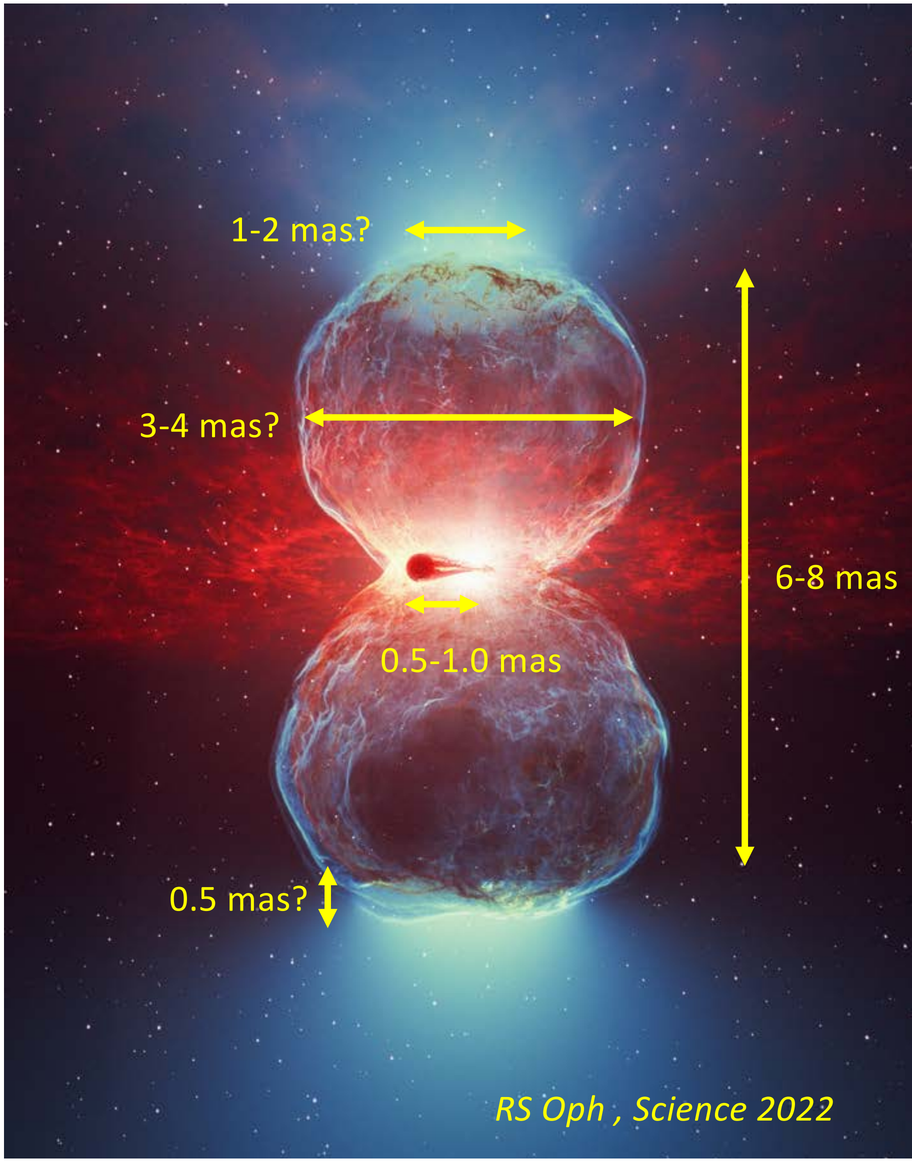
What is the driving material?

Other angular scales may have longer timescales





Morgan, W. W., and Deutsch, A. J., 1947, Ap. J., 106, 362.
Herbig, G. H., and Neubauer, E. J., 1946, P, A. S. P., 58, 196.
McLaughlin, D. B., 1946, P. A. S. P., 58, 159.
Sanford, R. F.. 1947, P. A. S. P., 59, 87, 334.
Bloch, M., Dufay, J., Fehrenbach, C., and Tcheng Mao-Lin, 1946, Ann. d'Ap., 9, 157.



T Cor Bor angular scales

If T Cor Bor is not a simple bubble, might have structure on several angular scales.

RS Oph Model (Science 2022)

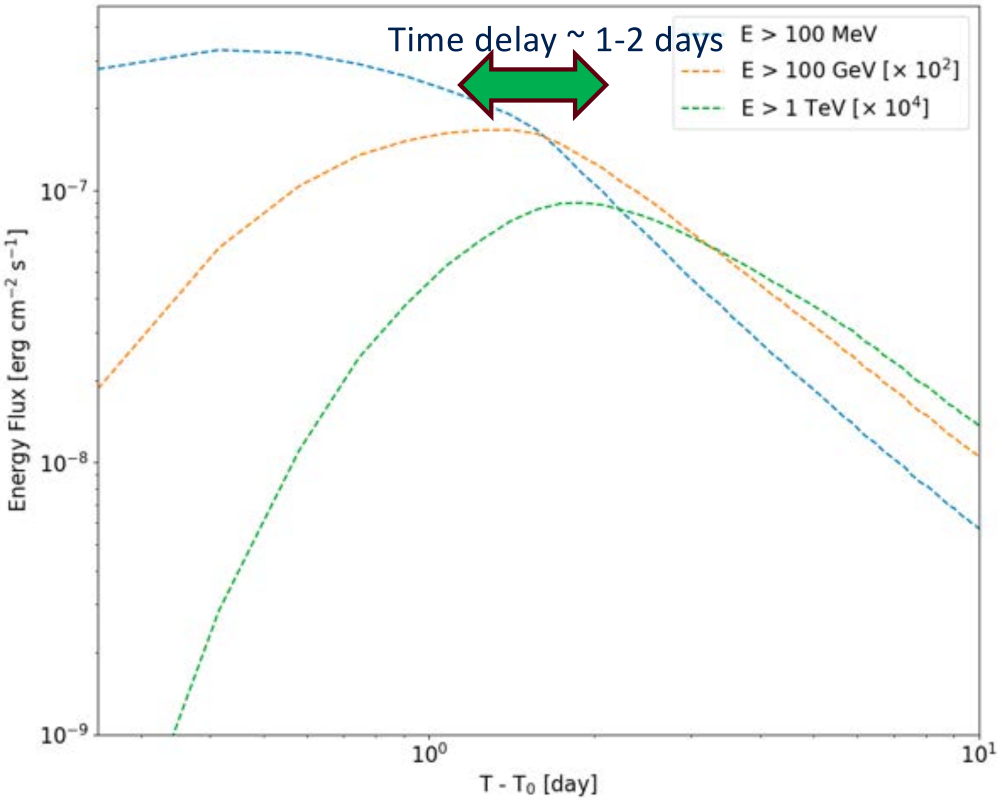
½ distance to RS Oph : expect 2X angular scale

Measured RS Oph: 3-4 mas -> T Cor Bor 6-8 mas

Other angular scales: RG-WD separation: 0.5 -1.0 mas
bubble width: 3-4 mas
emission regions: 0.5 mas x 1-2 mas
Source asymmetry due to orbital plane gas

Any constraints on the angular scales of optical emission can be helpful ….

T Cor Bor GeV/TeV emission

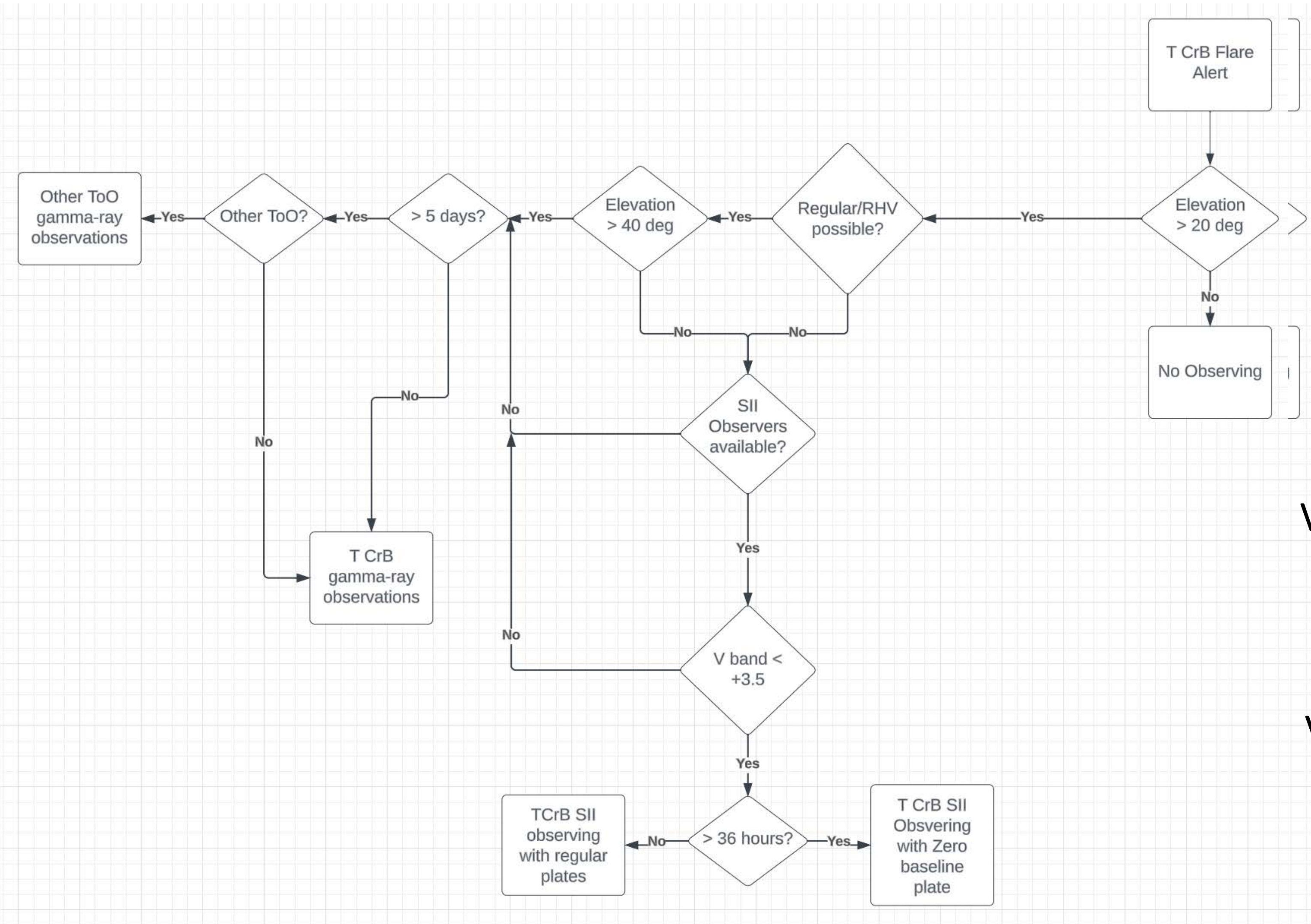


Expect similar time dependent GeV/TeV emission

Expect peak T Cor Bor GeV/TeV to be >4x brighter than RS Oph

Expect faster evolution that RS Oph (1-2 days between GeV to TeV peaks)

Need to observe in VHE immediately when it goes off…..



Near Simultaneous Veritas Observations of VHE & SII

Coordinating a joint VHE/SII campaign with MAGIC, LST

VSII Science Plans 2024

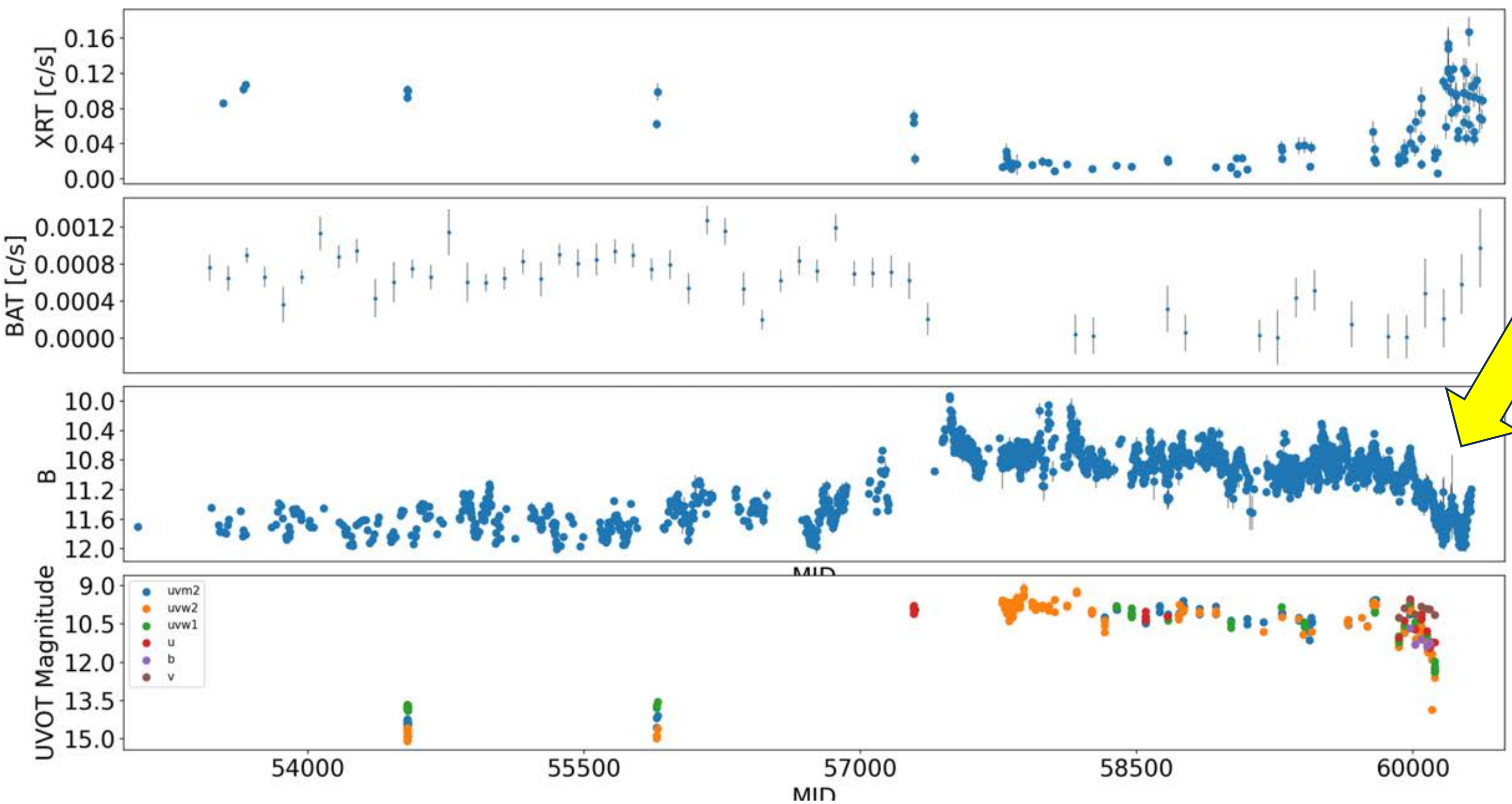
- 2-D analysis of Fast Rotators (gamma Cassiopeiae) -**Now**
- Analyze & Publish. archival survey data 2019 – 2024 **– Dec 2024**
- Joint VHE/SII T Cor Bor and other nova (if lucky) **TBD**

- Approaching 1% resolution in visibility curve
  - Improvements in 1-D & 2-D fast rotator analysis
  - Explore Limb Darkening constraints (Dark Time observations?)
  - Multi-orbit observations of short term binaries (days/weeks)
  - Model dependent fitting of general 2-D images (binaries)
  - We still have room to improve……

- Technology & simulation development for SII-CTA implementation

- Archive data in community available forum with standard tools (eg. OIFITS)

MW monitoring of T Cor Bor

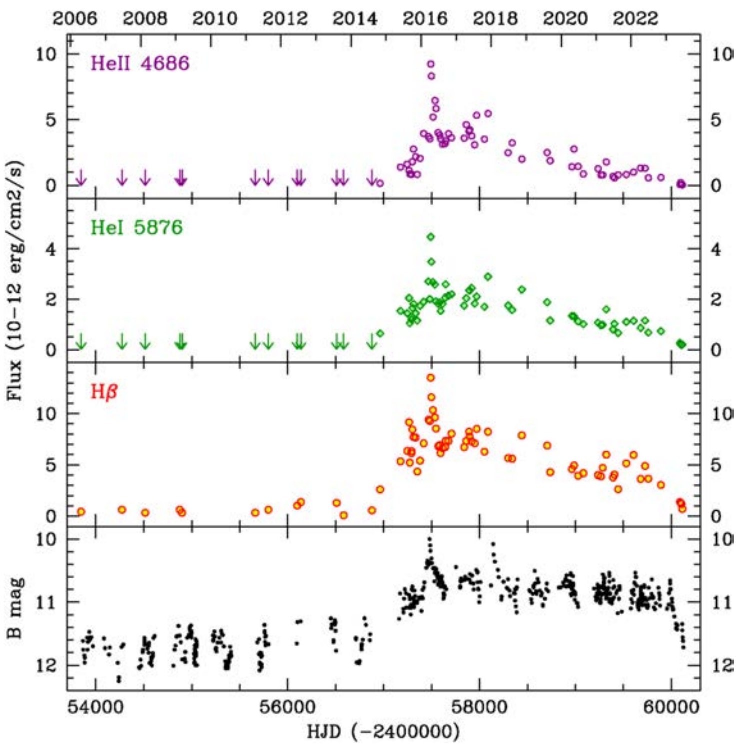


B dimming
In Fall 2023

Precursor
seen in 1947

2024.4 ± 0.3

Predicted Eruption: 2024.4 +/- 0.3



Ulisse Munari 2023 *Res. Notes AAS* **7** 145

M_V~2.0 only for a few days

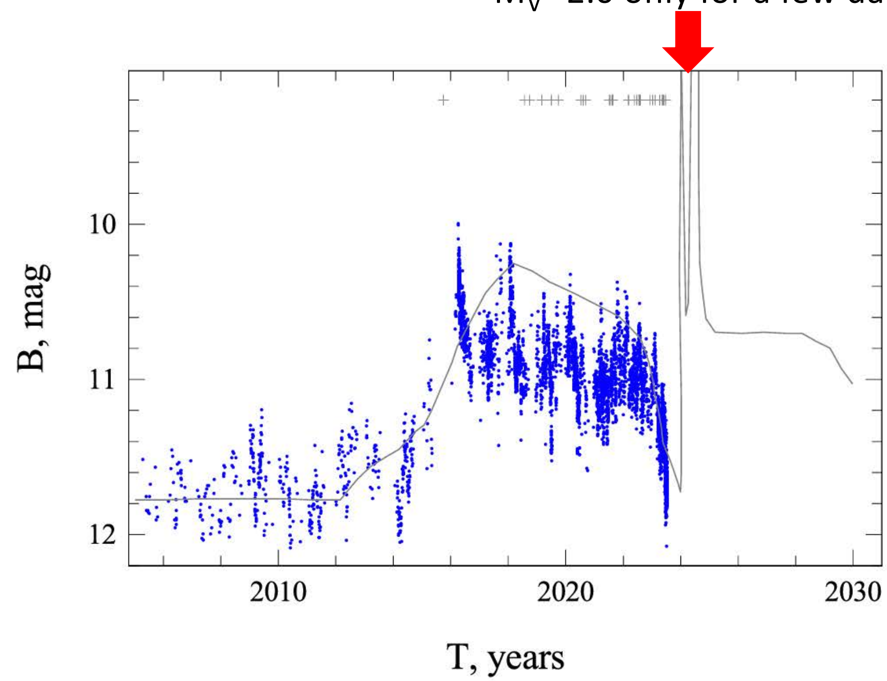


Figure 10: The *B*-band light curve of T CrB composed of AAVSO data (dots). The black line represents the averaged light curve of the 1946 eruption of T CrB from Schaefer (2023), the crosses indicate the moments of Swift-UVOT observations.

N.A. Maslennikova, Astronomy Letters (2023)